D. INSTRUMENTATION AND MEASUREMENT TECHNIQUES

D.1 Introduction

This appendix provides information on various field and laboratory equipment used to measure radiation levels and radioactive material concentrations. The descriptions provide information pertaining to the general types of available radiation detectors and the ways in which those detectors are utilized for various circumstances. Similar information may be referenced from MARSSIM Appendix H, Description of Field Survey and Laboratory Analysis Equipment (MARSSIM 2002), and NUREG-1761 Appendix B, Advanced/Specialized Information (NRC 2002). The information in this appendix is specifically designed to assist the user in selecting the appropriate radiological instrumentation and measurement technique during the implementation phase of the Data Life Cycle (Chapter 5).

The following topics will be discussed for each instrumentation and measurement technique combination:

- **Instruments** – a description of the equipment and the typical detection instrumentation it employs
- **Temporal Issues** – a synopsis of time constraints that may be encountered through use of the measurement technique
- **Spatial Issues** – limitations associated with the size and portability of the instrumentation as well as general difficulties that may arise pertaining to source-to-detector geometry
- **Radiation Types** – applicability of the measurement technique for different types of ionizing radiation
- **Range** – the associated energy ranges for the applicable types of ionizing radiation
- **Scale** – typical sizes for the M&E applicable to the measurement technique

- **Ruggedness** – a summary of the durability of the instrumentation (note that this is frequently limited by the detector employed by the instrumentation; e.g., an instrument utilizing a plastic scintillator is inherently more durable than an instrument utilizing a sodium iodide crystal); suitable temperature ranges for proper operation of the instrumentation and measurement technique have been provided where applicable

D.2 General Detection Instrumentation

This section summarizes the most common detector types used for the detection of ionizing radiation in the field. This will discuss many of the detector types incorporated into the measurement methods that are described in later sections of this chapter.

D.2.1 Gas-Filled Detectors

Gas-filled detectors are the most commonly-used radiation detectors and include gas-ionization chamber detectors, gas-flow proportional detectors, and Geiger-Muller (GM) detectors. These detectors can be designed to detect alpha, beta, photon, and neutron radiation. They generally consist of a wire passing through the center of a gas-filled chamber with metal walls, which can be penetrated by photons and high-energy beta particles. Some chambers are fitted with mylar windows to allow penetration by alpha and low-energy beta radiation. A voltage source is connected to the detector with the positive terminal connected to the wire and the negative terminal connected to the chamber casing to generate an electric field, with the wire serving as the anode, and the chamber casing serving as the cathode. Radiation ionizes the gas as it enters the chamber, creating free electrons and positively-charged ions. The number of electrons and positively-charged ions created is related to the properties of the incident radiation type (alpha particles produce many ion pairs in a short distance, beta particles produce fewer ion pairs due to their smaller size, and photons produce relatively few ion pairs as they are uncharged and interact with the gas significantly less than alpha and beta radiation). The anode attracts the free electrons while the cathode attracts the positively charged ions. The reactions between these ions and free electrons with either the anode or cathode produce disruptions in the electric field. The voltage applied to the chamber can be separated into different voltage ranges that distinguish the types of gas-filled detectors described below. The different types of gas-filled detectors are described in ascending order of applied voltage.

D.2.1.1 Ionization Chamber Detectors

Ionization chamber detectors consist of a gas-filled chamber operated at the lowest voltage range of all gas-filled detectors.[1] Ionization detectors utilize enough voltage to provide the ions with sufficient velocity to reach the anode or cathode. The signal pulse heights produced in ionization chamber detectors is small and can be discerned by the external circuit to differentiate between different types of radiation. These detectors provide true measurement data of energy deposited proportional to the charge produced in air, unlike gas-flow proportional and GM detectors which are detection devices. These detectors are generally designed to collect cumulative beta and photon radiation without amplification and many have a beta shield to help distinguish between these radiation types. These properties make ionization detectors excellent choices for measuring exposure rates from photon emission radiation in roentgens. These detectors can be deployed for an established period of time to collect data in a passive manner for disposition surveys. Ionization chamber detectors may assist in collecting measurements in inaccessible areas due to their availability in small sizes.

Another form of the ionization chamber detector is the pressurized ion chamber (PIC). As with other ionization chamber detectors, the PIC may be applied for M&E disposition surveys when a exposure-based action level is used. The added benefit of using PICs is that they can provide more accurate dose measurements because they compensate for the various levels of photon energies as opposed to other exposure rate meters (e.g., micro-rem meter), which are calibrated to a ^{137}Cs source. PICs can be used to cross-calibrate other exposure rate detectors applicable for surveying M&E, allowing the user to

[1] At voltages below the ionization chamber voltage range, ions will recombine before they can reach either the cathode or anode and do not produce a discernable disruption to the electric field.

compensate for different energy levels and reduce or eliminate the uncertainty of underestimating or overestimating the exposure rate measurements.

D.2.1.2 Gas-Flow Proportional Detectors

The voltage applied in gas-flow proportional detectors is the next range higher than ionization chamber detectors, and is sufficient to create ions with enough kinetic energy to create new ion pairs, called secondary ions. The quantity of secondary ions increases proportionally with the applied voltage, in what is known as the gas amplification factor. The signal pulse heights produced can be discerned by the external circuit to differentiate between different types of radiation. Gas-flow proportional detectors are generally used to detect alpha and beta radiation. Systems also detect photon radiation, but the detection efficiency for photon emissions is considerably lower than the relative efficiencies for alpha and beta activity. Physical probe areas for these types of detectors vary in size from approximately 100 cm^2 up to 600 cm^2. The detector cavity in these instruments is filled with P-10 gas which is an argon-methane mixture (90% argon and 10% methane). Ionizing radiation enters this gas-filled cavity through an aluminized mylar window. Additional mylar shielding may be used to block alpha radiation; a lower voltage setting may be used to detect pure alpha activity (NRC 1998b).

D.2.1.3 Geiger-Mueller Detectors

GM detectors operate in the voltage range above the proportional range and the limited proportional range.[2] This range is characterized by extensive gas amplification that results in what is referred to as an "avalanche" of ion and electron production. This mass production of electrons spreads throughout the entire chamber, which precludes the ability to distinguish between different kinds of radiation because all of the signals produced are the same size. GM detectors are most commonly used for the detection of beta activity, though they may also detect both alpha and photon radiation. GM detectors have relatively short response and dead times and are sensitive enough to broad

[2] The limited proportional range produces secondary ion pairs but does not produce reactions helpful for radiation detection, because the gas amplification factor is no longer constant.

detectable energy ranges for alpha, beta, photon, and neutron emissions (though they cannot distinguish which type of radiation produces input signals) to allow them to be used for surveying M&E with minimal process knowledge.[3]

GM detectors are commonly divided into three classes: "pancake", "end-window", and "side-wall" detectors. GM pancake detectors (commonly referred to as "friskers") have wide diameter, thin mica windows (approximately 15 cm^2 window area) that are large enough to allow them to be used to survey many types of M&E. Although GM pancake detectors are referenced beta and gamma detectors, the user should consider that their beta detection efficiency far exceeds their gamma detection efficiency. The end-window detector uses a smaller, thin mica window and is designed to allow beta and most alpha particles to enter the detector unimpeded for concurrent alpha and beta detection. The side-wall detector is designed to discriminate between beta and gamma radiation, and features a door that can be slid or rotated closed to shield the detector from beta emissions for the sole detection of photons. These detectors require calibration to detect for beta and gamma radiation separately. Energy-compensated GM detectors may also be cross-calibrated for assessment of exposure rates.

D.2.2 Scintillation Detectors

Scintillation detectors (sometimes referred to as "scintillators") consist of scintillation media that emits a light "output" called a scintillation pulse when it interacts with ionizing radiation. Scintillators emit low-energy photons (usually in the visible light range) when struck by high-energy charged particles; interactions with external photons cause scintillators to emit charged particles internally, which in turn interact with the crystal to emit low-energy photons. In either case, the visible light emitted (i.e., the low-energy photons) are converted into electrical signals by photomultiplier tubes and recorded by a digital readout device. The amount of light emitted is generally

[3] GM detectors may be designed and calibrated to detect alpha, beta, photon, and neutron radiation, though they are much better-suited for the detection of charged particles (i.e., alpha and beta particles) than neutral particles (i.e., photons and neutrons).

proportional to the amount of energy deposited, allowing for energy discrimination and quantification of source radionuclides in some applications.

D.2.2.1 Zinc Sulfide Scintillation Detectors

Zinc sulfide detector crystals are only available as a polycrystalline powder that are arranged in a thin layer of silver-activated zinc sulfide (ZnS(Ag)) as a coating or suspended within a layer of plastic scintillation material. The use of these thin layers makes them inherently-dispositioned for the detection of high linear energy transfer (LET) radiation (radiation associated with alpha particles or other heavy ions). These detectors use an aluminized mylar window to prevent ambient light from activating the photomultiplier tube (Knoll 1999). The light pulses produced by the scintillation crystals are amplified by a photomultiplier tube, converted to electrical signals, and counted on a digital scaler/ratemeter. Low LET radiations (particularly beta emissions) are detected at much lower detection efficiencies than alpha emissions and pulse characteristics may be used to discriminate beta detections from alpha detections.

D.2.2.2 Sodium Iodide Scintillation Detectors

Sodium iodide detectors are well-suited for detection of photon radiation. Energy-compensated sodium iodide detectors may also be cross-calibrated for assessment of exposure rates. Unlike ZnS(Ag), sodium iodide crystals can be grown relatively large and machined into varying shapes and sizes. Sodium iodide crystals are activated with trace amounts of thallium (hence the abbreviation NaI(Tl)), the key ingredient to the crystal's excellent light yield (Knoll, 1999). These instruments most often have upper- and lower-energy discriminator circuits and when used correctly as a single-channel analyzer, can provide information on the photon energy and identify the source radionuclides. Sodium iodide detectors can be used with handheld instruments or large stationary radiation monitors.

D.2.2.3 Cesium Iodide Scintillation Detectors

Cesium iodide detectors are generally similar to sodium iodide detectors. Like NaI(Tl), cesium iodide may be activated with thallium (CsI(Tl)) or sodium (CsI(Na)). Cesium iodide is more resistant to shock and vibration damage than NaI, and when cut into thin sheets it features malleable properties allowing it to be bent into various shapes. CsI(Tl) has variable decay times for various exciting particles, allowing it to help differentiate between different types of ionizing radiation. A disadvantage of CsI scintillation detectors is due to the fact that the scintillation emission wavelengths for CsI are longer than those produced by sodium iodide crystals; since almost all photomultiplier tubes are designed for NaI, there are optical incompatibilities that result in decreased intrinsic efficiencies for CsI detectors. Additionally, CsI scintillation detectors feature relatively long response and decay times for luminescent states in response to ionizing radiation (Knoll 1999).

D.2.2.4 Plastic Scintillation Detectors

Plastic scintillators are composed of organic scintillation material that is dissolved in a solvent and subsequently hardened into a solid plastic. Modifications to the material and specific packaging allow plastic scintillators to be used for detecting alpha, beta, photon, or neutron radiation. While plastic scintillators lack the energy resolution of sodium iodide and some other gamma scintillation detector types, their relatively low cost and ease of manufacturing into almost any desired shape and size enables them to offer versatile solutions to atypical radiation detection needs (Knoll 1999).

D.2.3 Solid State Detectors

Solid state detection is based on ionization reactions within detector crystals composed of an electron-rich (n-type or electron conductor) sector and an electron-deficient (p-type or hole conductor) sector. Reverse-bias voltage is applied to the detector crystal; forming a central region absent of free charge (this is termed the depleted region). When a particle enters this region, it interacts with the crystal structure to form hole-electron pairs. These holes and electrons are swept out of the depletion region to the positive and negative electrodes by the electric field, and the magnitude of the resultant pulse in the external circuit is directly proportional to the energy lost by the ionizing radiation in the depleted region.

Solid state detection systems typically employ silicon or germanium crystals[4] and utilize semiconductor technology (i.e., a substance whose electrical conductivity falls between that of a metal and that of an insulator, and whose conductivity increases with decreasing temperature and with the presence of impurities). Semiconductor detectors are cooled to extreme temperatures to utilize the crystal material's insulating properties to prevent thermal generation of noise. The use of semiconductor technology can achieve energy resolutions, spatial resolutions, and signal-to-noise ratios superior to those of scintillation detection systems.

D.3 Counting Electronics

Instrumentation requires a device to accumulate and record the input signals from the detector over a fixed period of time. These devices are usually electronic, and utilize scalers or rate-meters to display results representing the number of interaction events (between the detector and radionuclide emissions) within a period of time (e.g., counts per minute). A scaler represents the total number of interactions within a fixed period of time, while a rate-meter provides information that varies based on a short-term average of the rate of interactions.

Scalers represent the simpler of these two counting approaches, because they record a single count each time an input signal is received from the detector. Scaling circuits are typically designed with scalers to allow the input signals to be cut by factors of 10, 100, or 1,000 to allow the input signals to be counted directly by electromechanical registers when counting areas with elevated radioactivity. Scalers are generally used when taking in situ measurements and are used to determine average activities.

Contemporary rate-meters utilize analog-to-digital converters to sample the pulse amplitude of the input signal received from the detector and convert it to a series of digital values. These digital values may then be manipulated using digital filters (or shapers) to average or "smooth" the data displayed. The counting-averaging technique

[4] Solid state detection systems may also utilize crystals composed of sodium iodide, cesium iodide, or cadmium zinc telluride in non-semiconductor applications.

used by rate-meters may be more helpful than scalers in identifying elevated activity. When using scalers in performing scanning surveys to locate areas of elevated activity, small areas of elevated activity may appear as very quick "blips" that are difficult to discern, while rate-meters continue to display heightened count rates once the detector has moved past the elevated activity, and display "ramped up" count rates immediately preceding the elevated activity as well. Rate-meters have the inherent limitation in that the use of their counting electronics varies the signals displayed by the meter since they represent a short-term average of the event rate. It is conceivable that very small areas of elevated activity (e.g., particle) might have their true activity concentrations "diluted" by the averaging of rate-meter counting electronics.

D.4 Hand-Held Instruments

This section discusses hand-held instruments, which may be used for in situ measurements or scanning surveys.

D.4.1 Instruments

In situ measurements with hand-held instruments are typically conducted using the detector types described in Section D.2. These typically are composed of a detection probe (utilizing a single detector) and an electronic instrument to provide power to the detector and to interpret data from the detector to provide a measurement display.

The most common types of hand-held detector probes are GM detectors, ZnS(Ag) alpha/beta scintillation detectors, and NaI(Tl) photon scintillation detectors. There are instances of gas-flow proportional detectors as hand-held instruments, though these are not as common since these detectors operate using a continuous flow of P-10 gas, and the accessories associated with the gas (e.g., compressed gas cylinders, gauges, tubing) make them less portable for use in the field.

D.4.2 Temporal Issues

Hand-held instruments generally have short, simple equipment set-ups requiring minimal time, often less than ten minutes. In situ measurement count times typically range from 30 seconds to two minutes. Longer count times may be utilized to increase resolution and provide lower minimum detectable limits. Typical scanning speeds are approximately 2.5 centimeters per second. Slower scanning speeds will aid in providing lower minimum detectable concentrations.

D.4.3 Spatial Issues

Detectors of hand-held instruments are typically small and portable, having little trouble fitting into and measuring most M&E. Spatial limitations are usually based on the physical size of the probe itself. The user must be wary of curved or irregular surfaces of M&E being surveyed. Detector probes generally have flat faces and incongruities between the face of the detector and the M&E being surveyed have an associated uncertainty. ZnS scintillation and gas-flow proportional detectors are known to have variations in efficiency of up to 10% across the face of the detector. Therefore, the calibration source used should have an area at least the size of the active probe area.

D.4.4 Radiation Types

Assortments of hand-held instruments are available for the detection of alpha, beta, photon, and neutron radiations. Table D.1 illustrates the potential applications for the most common types of hand-held instruments.

D.4.5 Range

The ranges of detectable energy using hand-held instruments are dependent upon the type of instrument selected and type of radiation. Some typical detectable energy ranges for common hand-held instruments are listed above in Table D.1. More detailed information pertaining to the ranges of detectable energy using hand-held instruments are available in the European Commission for Nuclear Safety and the Environment Report 17624 (EC 1998).

Table D.1 Potential Applications for Common Hand-Held Instruments

	Alpha	Beta	Photon	Neutron	Detectable Energy Range	
					Low End Boundary	High End Boundary
Ionization chamber detectors	NA	FAIR	GOOD	NA	40-60 keV	1.3-3 MeV
Gas-flow proportional detectors	GOOD	GOOD	POOR	POOR	5-50 keV	8-9 MeV
Geiger-Muller detectors	FAIR	GOOD	POOR	POOR	30-60 keV	1-2 MeV
ZnS(Ag) scintillation detectors	GOOD	POOR	NA	NA	30-50 keV	8-9 MeV
NaI(Tl) scintillation detectors	NA	POOR	GOOD	NA	40-60 keV	1.3-3 MeV
NaI(Tl) scintillation detectors (thin detector, thin window)	NA	FAIR	GOOD	NA	10 keV	60-200 keV
CsI(Tl) scintillation detectors	NA	POOR	GOOD	NA	40-60 keV	1.3-3 MeV
Plastic scintillation detectors	NA	FAIR	GOOD	NA	40-60 keV	1.3-3 MeV
BF_3 proportional detectors[5]	NA	NA	NA	GOOD	0.025 eV	100 MeV
^3He proportional detectors[5]	NA	NA	POOR	GOOD	0.025 eV	100 MeV

Notes:

GOOD The instrument is well-suited for detecting this type of radiation

FAIR The instrument can adequately detect this type of radiation

POOR The instrument may be poorly-suited for detecting this type of radiation

NA The instrument cannot detect this type of radiation

D.4.6 Scale

There is no definitive limit to the size of an object to be surveyed using hand-held instruments. Hand-held instruments may generally be used to survey M&E of any size; constraints are only placed by the practical sizing of M&E related to the sensitive area of the probe. Limitations may also be derived from the physical size of the detector probes

[5] The use of moderators enables the detection of high-energy fast neutrons. Either BF_3 or ^3He gas proportional detectors may be used for the detection of fast neutrons, but ^3He are much more efficient in performing this function. BF_3 detectors discriminate against gamma radiation more effectively than ^3He detectors.

used for surveying. The largest hand-held detector probes feature effective detection surface areas of approximately 175 to 200 cm^2. Detection probes larger than this may be of limited use with hand-held instruments.

D.4.7 Ruggedness

All varieties of hand-held instruments discussed here are typically calibrated for use in temperatures with lower ranges from -30 ° to -20 °C and upper ranges from 50 ° to 60 °C. The durability of a hand-held instrument depends largely upon the detection media (crystals, such as sodium iodide and germanium crystals are fragile and vulnerable to mechanical and thermal shock) and the presence of a mylar (or similar material) window:

- **Ionization chamber detectors** – ionization chamber detectors are susceptible to physical damage and may provide inaccurate data (including false positives) if exposed to mechanical shock.
- **Gas-flow proportional detectors** – detection gas used with gas-flow proportional detectors may leak from seals such that these detectors are usually operated in the continuous gas flow mode; the use of flow meter gauges to continuously monitor the gas flow rate is recommended along with frequent quality control checks to ensure the detector still meets the required sensitivity; gas-flow proportional detectors may also use fragile mylar windows to contain the detection gases, which renders the detectors vulnerable to puncturing and mechanical shock.
- **Geiger-Muller detectors** – GM tubes typically use fragile mylar windows to contain the detection gases; the presence of a mylar window renders the detector vulnerable to puncturing and mechanical shock.
- **ZnS(Ag) scintillation detectors** – zinc sulfide is utilized as thin-layer polycrystalline powder in detectors and are noted for being vulnerable to mechanical shock; zinc sulfide detectors may use fragile mylar windows, in which case the detector is vulnerable to puncturing and mechanical shock.
- **NaI(Tl) scintillation detectors** – sodium iodide crystals are relatively fragile and can be damaged through mechanical shock; sodium iodide is also highly

hydroscopic such that the crystals must remain environmentally sealed within the detector housing.

- **Plastic Scintillation Detectors** – plastic scintillators are typically robust and resistant to damage from mechanical and thermal shock.

D.5 Volumetric Counters (Drum, Box, Barrel, Four Pi Counters)

The term Box Counter is a generic description for a radiation measurement system that typically involves large area, four pi (4π) radiation detectors and includes the following industry nomenclature: tool counters, active waste monitors, surface activity measurement systems, and bag/barrel/drum monitors. Box counting systems are most frequently used for conducting in situ surveys of M&E that is utilized in radiologically-controlled areas. These devices are best-suited for performing gross activity screening measurements on Class 2 and Class 3 M&E (NRC 2002). Typical items to be surveyed using box counters are hand tools, small pieces of debris, bags of trash, and waste barrels. Larger variations of box counting systems can count objects up to a few cubic meters in size.

D.5.1 Instruments

Box counting systems typically consist of a counting chamber, an array of detectors configured to provide a 4π counting geometry, and microprocessor-controlled electronics that allow programming of system parameters and data-logging. Systems typically survey materials for photon radiation and usually incorporate a shielded counting chamber and scintillation detectors (plastic scintillators or sodium iodide scintillation detectors). These systems most commonly utilize four or six detectors, which are situated on the top, bottom, and sides of the shielded counting chamber (Figure D.1). Some systems monitor M&E for beta activity, using a basic design similar to photon radiation detection systems, but utilizing gas-flow proportional counters. In rare cases, neutron detection has been used for criticality controls and counter-proliferation screening.

Figure D.1 Example Volumetric Counter (Thermo 2005)

Box counting systems for alpha activity feature a substantial departure in design from beta/gamma detection systems. Alpha activity systems do not require heavy shielding to filter out ambient sources of radiation. These devices utilize air filters to remove dust and particulates from air introduced into counting chambers that incorporate airtight seals. Filtered air introduced into the counting chamber interacts with any surface alpha activity associated with the M&E.

Each alpha interaction with a surrounding air molecule produces an ion pair. These ion pairs are produced in proportion to the alpha activity per unit path length. This air (i.e., the ion pairs in the air) is then counted using an ion detector for quantification of the specific activity. The specific activity of the air in the counting chamber provides a total surface activity quantification for the M&E (BIL 2005).

D.5.2 Temporal Issues

Typically, box counting systems require approximately one to 100 seconds to conduct a measurement (Thermo 2005). The count times are dependent on a number of factors to include required measurement sensitivity and background count rates with accompanying subtraction algorithms. The count times for box counting are typically considered relatively short for most disposition surveys.

D.5.3 Spatial Issues

Since box counters typically average activity over the volume or mass of the M&E, the spatial distribution of radioactivity may be a significant limitation on the use of this measurement technique. The design of box counting systems is not suited to the identification of localized elevated areas, and therefore may not be the ideal choice when the disposition criteria is not based on average or total activity.

Some systems incorporate a turntable inside the counting chamber to improve measurement of difficult-to-measure areas or for heterogeneously distributed radioactivity. When practical, performing counts on objects in two different orientations (i.e., by rotating the M&E 90 or 180 degrees and performing a subsequent count) will yield more thorough and defensible data.

Proper use of box counters includes segregating the M&E to be surveyed and promoting accurate measurements through uniform placement of items to be surveyed in the counting chamber. For example, a single wrench placed on its side in a box counter has different geometric implications from a tool of similar size standing up inside the counting chamber. Counting jigs for sources and M&E to be surveyed are frequently employed to facilitate consistent, ideal counting positions between the M&E and the counting chamber detector array.

D.5.4 Radiation Types

Box counting systems are intrinsically best-suited for the detection of moderate- to high-energy photon radiation. As described in Section D.5.1, specific systems may be designed for the detection of low-energy photon, beta, alpha, and in some cases neutron radiation. For proper calibration and utilization of box counters, it is often necessary to establish the radiation types and anticipated energy ranges prior to measurement.

D.5.5 Range

Photon radiation can typically be measured within a detectable energy range of 40 to 60 keV up to 1.3 to 3 MeV. For example, typical box counters positioned at radiological control area exit points are configured to alarm at a set point of 5,000 dpm total activity. The precise count time is adjusted automatically by setting the predetermined count rate to limit the error. Measurement times will range from 5 to 45 seconds in order to complete counts of this kind, depending on current background conditions (Thermo 2005). Lower detection capabilities are achievable by increasing count times or incorporating background reduction methodologies.

D.5.6 Scale

Size limitations pertaining to the M&E to be surveyed are inherently linked to the physical size of the counting chamber. Smaller box counting systems have a counting chamber of less than 0.028 cubic meters (approximately one cubic foot) and are often used for tools and other frequently-used small items. The maximum size of box counters is typically driven by the logistics of managing the M&E to be measured, and this volume is commonly limited to a 55-gallon waste drum. Some box counting systems allow counts to be performed on oversized items protruding from the counting chamber with the door open.

D.5.7 Ruggedness

Many volumetric counter models feature stainless steel construction with plastic scintillation detectors and window-less designs, which translates to a rugged instrument that is resistant to mechanical shock.

D.6 Conveyorized Survey Monitoring Systems

Conveyorized survey monitoring systems automate the routine scanning of M&E. Conveyorized survey monitoring systems have been designed to measure materials such as soil, clothing (laundry monitors), copper chop (small pieces of copper), rubble, and debris. Systems range from small monitoring systems comprised of a single belt that passes materials through a detector array, to elaborate multi-belt systems capable of measuring and segregating material while removing extraneously-large items. The latter type comprises systems that are known as segmented gate systems. These automated scanning systems segregate materials by activity by directing material that exceeds an established activity level onto a separate conveyor. Simpler conveyorized survey monitoring systems typically feature an alarm/shut-down feature that halts the conveyor motor and allows for manual removal of materials that have exceeded the established activity level.

D.6.1 Instruments

A typical conveyorized survey monitoring system consists of a motorized conveyor belt that passes materials through an array of detectors, supporting measurement electronics, and an automated data-logging system (Figure D.2). Systems typically survey materials for photon radiation and usually incorporate scintillation detectors (plastic scintillators or sodium iodide scintillation detectors) or high-purity germanium detectors. Scintillation detector arrays are often chosen for gross gamma activity screening. Conveyorized survey monitoring systems designed to detect radionuclide mixtures with a high degree of process knowledge work best using plastic scintillators, while systems categorizing material mixtures where the radionuclide concentrations are variable are better-suited to the use of sodium iodide scintillation detectors. Conveyorized survey monitoring systems designed for material mixtures where the radionuclide concentrations are unknown may be suitable for more expensive and maintenance-intensive high-purity germanium detector arrays, which will allow for quantitative measurement of complex photon energy spectra. An alternative method for screening materials for different photon energy regions of interest is to incorporate sodium iodide detector arrays with crystals of varying thickness to target multiple photon energies. Systems may also be fitted with gas flow proportional counters for the detection of alpha and beta emissions. Laundry conveyorized survey monitoring systems are typically designed for the detection of alpha and beta radiation, as the nature of clothes allows the survey media to be compressed, allowing the detector arrays to be close to or in contact with the survey media.

Figure D.2 Example Conveyorized Survey Monitoring System (Laurus 2001)

D.6.2 Temporal Issues

Typically, conveyorized survey monitoring systems require approximately one to six seconds to count a given field of detection (Novelec 2001a). Systems are designed to provide belt speeds ranging from 0.75 meters up to 10 meters (2.5 to 33 feet) per minute to accommodate the necessary response time for detection instrumentation (Thermo 2006; Eberline 2004). This yields processing times of 15 to 45 metric tons (16 to 50 tons) of material per hour for soil or construction demolition-type material conveyorized survey monitoring systems (NRC 2002).

D.6.3 Spatial Issues

The M&E that are typically surveyed by conveyorized survey monitoring systems may contain difficult-to-measure areas. Most systems employ the detector arrays in a staggered, off-set configuration, which allows the sensitive areas of the detectors to overlap with respect to the direction of movement. This off-set configuration helps to eliminate blind spots (i.e., locations where activity may be present but cannot be detected because the radiation cannot reach the detectors). Some systems are designed specifically for materials of relatively small particles of uniform size (e.g., soil), while others have been designed to accommodate heterogeneous materials like rubble and debris.

The data logging system accepts the signal pulses from the detector systems and stores the pulse data in counting scalers. The recorded values are continuously compared with pre-set alarm values corresponding to the selected action level(s). The detectors incorporate integral amplifiers which are routed to a PC containing multi-channel scaler hardware. The multi-channel scaler hardware allows data to be collected in a series of short, discrete scaler channels known as "time bins". The count time for each time bin is selected as a function of the speed of the conveyor belt. The time bin length is frequently set up to be half the length of "dwell time," which is the time the material aliquot to be surveyed spends within the detection field (Miller 2000).

The approach cited in the paragraph above ensures that activity present within the survey unit will be in full view of the detector for one complete time bin. Data collection is optimized by performing the measurement when the activity is concentrated (i.e., within an area of elevated activity) as well as when the activity is approximately homogenously-distributed within a given material aliquot.

D.6.4 Radiation Types

Conveyorized survey monitoring systems are generally best-suited for the detection of photon radiation. Specific systems may be tailored for the detection of beta emissions of moderate energy and even alpha radiation by employing gas flow proportional counter detector arrays.

D.6.5 Range

Photon radiation can typically be measured with a detectable energy range from 50 keV up to 2 MeV. Conveyorized survey monitoring systems equipped to measure alpha and beta emissions can typically measure from 100 keV up to 6 MeV.

D.6.6 Scale

Most conveyorized survey monitoring systems are designed for soils or laundry, both of which are compressible media. Applicable sample/material heights range from 2 cm to 12.5 cm (Life Safety 2005).

D.6.7 Ruggedness

Conveyorized survey monitoring systems have typical operating ranges from -20° C to 50° C. Conveyorized survey monitoring systems are often constructed from steel and with plastic scintillation detectors and windowless designs, which makes them generally resistant to damage from extraneous pieces of debris during scanning. Mechanical shock is not a typical concern for conveyorized survey monitoring systems because there is little need for moving these systems. For this reason conveyorized survey monitoring systems are seldom transported from one location to another.

D.7 In Situ Gamma Spectroscopy

In situ gamma spectroscopy (ISGS) systems combine the peak resolution capabilities of laboratory methods with instrumentation that is portable and rugged enough to be used in field conditions. These solid state systems can perform quantitative, multi-channel analysis of gamma-emitting isotopes in both solid and liquid media over areas as large as 100 m^2, enabling spectrographic analysis of M&E that assists the user in identifying constituent radionuclides and differentiating them from background radiation. ISGS system measurements can also provide thorough coverage within broad survey areas, minimizing the risk of failing to detect isolated areas of elevated radioactivity that could potentially be missed when collecting discrete samples.

D.7.1 Instruments

ISGS systems consist of a semiconductor detector, a cryostat, a multi-channel analyzer (MCA) electronics package that provides amplification and analysis of the energy pulse heights, and a computer system for data collection and analysis. Semiconductor detection systems typically employ a cryostat and a Dewar filled with liquid nitrogen (-196 °C). The cryostat transmits the cold temperature of the liquid nitrogen to the detector crystal, creating the extreme cold environment necessary for correct operation of the high-resolution semiconductor diode. ISGS systems may have electronic coolers as well.

ISGS systems use detectors referred to as N- and P-type detectors. N-type detectors contain small amounts of elements with five electrons in their outer electron shell (e.g., phosphorus, arsenic) within the germanium crystal (the inclusion of these elements within the germanium crystal is called "doping"). These result in free, unbonded electrons in the crystalline structure, providing a small negative current. P-type detectors utilize elements with less than four electrons in their outer electron shell (e.g., lithium, boron, gallium) are also used in doping to create electron holes, providing a small positive current. Use of these two varieties of doped germanium crystals provide different detection properties described below in Section D.7.5.

D.7.2 Temporal Issues

Setup for ISGS semiconductor systems may require one full day. The systems often require one hour to set up physically, six to eight hours for the semiconductor to reach the appropriate temperature operating range after the addition of liquid nitrogen, and quality control measurements may require another hour.[6] Count times using ISGS semiconductor systems tend to be longer than those associated with simpler detector systems for conducting static measurements, though this may be off-set by enlarging the field-of-view. A measurement time of several minutes is common, depending on the intensity of the targeted gamma energies and the presence of attenuating materials.

Count times can be shortened by reducing the distance between the area being surveyed and the detector to improve the gamma incidence efficiency or by using a larger detector. Each option will ultimately help the detection system see more gamma radiation in a shorter time. Yet either approach creates greater uncertainty associated with the source-to-detector geometry. A slight placement error (e.g., a 0.5 cm placement error) will result in significantly higher quantification error at a distance of one centimeter than at a distance of 10 centimeters. Additionally, this technique for decreasing count times promotes an effect called cascade summing, a phenomena affecting detection of gamma radiation from radionuclides that emit multiple gamma photons in a single decay event (e.g., ^{60}Co, which yields gamma particles of 1.17 and 1.33 MeV). If both incident gammas deposit their energy in a relatively short period of time (i.e., when compared to

[6] It is important not to move the apparatus prematurely, as failure to allow the ISGS system to cool and equilibrate to its proper operating temperatures as may cause damage to the semiconductor detector.

the detector response time and/or the resolving time for the associated electronics), limitations of the detection system may prevent these individual photons from being distinguished (Knoll 1999).

D.7.3 Spatial Issues

ISGS semiconductor systems require calibration for their intended use. While ISGS semiconductor systems can be calibrated using traditional prepared radioactive sources, some ISGS systems have software that enables the user to calculate efficiencies by entering parameters such as elemental composition, density, stand-off distance, and physical dimensions. Supplied geometry templates assist in generating calibration curves that can be applied to multiple collected spectra. The high resolution of these systems coupled with advanced electronic controls for system parameters allows them to overcome issues related to source-to-detector geometry and produce quantitative concentrations of multiple radionuclides in a variety of media (e.g., soil, water, air filters). Because ISGS systems integrate all radioactivity within their field-of-view, lead shielding and collimation may be required to "focus" the field-of-view on a specified target for some applications.

D.7.4 Radiation Types

ISGS systems can accurately identify and quantify only photon-emitting radionuclides.

D.7.5 Range

ISGS systems can identify and quantify low-energy gamma emitters (50 keV with P-type detectors, 10 keV with N-type detectors) and high-energy gamma emitters (ISGS systems can be configured to detect gamma emissions upwards of 2.0 MeV). Specially-designed germanium detectors that exhibit very little deterioration in resolution as a function of count rate use N-type detectors or planar crystals with a very thin beryllium window for the measurement of photons in the energy range 5 to 80 keV.

D.7.6 Scale

These systems therefore offer functional quantitative abilities to analyze small objects (e.g., samples) for radionuclides. They can also effectively detect radioactivity over areas as large as 100 m^2 or more (Canberra 2005a). With the use of an appropriate dewar, the detector may be used in a vertical orientation to determine gamma isotope concentrations in the ground surface and shallow subsurface.

D.7.7 Ruggedness

ISGS semiconductor systems are fragile, because the extremely low temperatures utilized by the cryostat render portions of the system brittle and susceptible to damage if not handled with care. Some ISGS systems are constructed of more rugged materials and their durability is comparable to most hand-held instruments.

D.8 Hand-Held Radionuclide Identifiers

Hand-held radionuclide identifiers represent a relatively new addition to the radiation detection market, merging the portability of hand-held instruments with some of the analytical capabilities of ISGS systems. Hand-held radionuclide identifiers also feature data logging and storage capabilities (including user-definable radionuclide libraries) and the ability to transfer data to external devices. These devices are most commonly used for nuclear non-proliferation, where immediate isotope identification is more critical than low-activity detection sensitivity. Design parameters for hand-held radionuclide identifiers required by ANSI N42.34 (ANSI 2003) are user-friendly controls and intuitive menu structuring for routine modes of operation, enabling users without health physics backgrounds (e.g., emergency response personnel) to complete basic exposure rate or radionuclide identification surveys. These units also feature restricted “expert” survey modes of operation to collect activity concentration data for more advanced applications, including disposition surveys.

D.8.1 Instruments

Hand-held radionuclide identifiers consist of two general types: integrated systems and modular systems. The integrated systems have the detector and electronics contained in a single package; modular systems separate the detector from the electronics. These spectrometers employ small scintillators, typically NaI(Tl) or CsI(Tl), or room temperature solid semiconductors, such as cadmium zinc telluride (CZT), linked to multi-channel analyzers and internal radionuclide libraries to enable gamma-emitting radionuclide identification.

D.8.2 Temporal Issues

Hand-held radionuclide identifiers require minimal time to set up.[7] Depending upon the conditions in which data is being collected (i.e., climatic, environmental, the presence of sources of radiological interference), it may require seconds to several minutes for the unit to stabilize the input signals from the field of radiation and properly identify the radionuclides.

D.8.3 Spatial Issues

Detectors of hand-held radionuclide identifiers are typically small and portable. Spatial limitations are usually based on the physical size of the probe itself, and whether the probe is coupled internally within the casing or externally via an extension cord.

D.8.4 Radiation Types

Hand-held radionuclide identifiers are most commonly used for the detection of photon radiation, although many devices have capabilities for detecting neutron and beta emissions (the detection of neutron radiation requires a different probe from the photon radiation probe).

D.8.5 Range

Photon radiation can typically be measured within a detectable energy range of 10 to 30 keV up to 2.5 to 3 MeV. Neutron radiation can typically be measured within a detectable energy range of 0.02 eV up to 100 MeV.

[7] The use of multi-point calibrations may add an estimated one to two hours to the time required for instrument set up.

D.8.6 Scale

There is no definitive limit to the size of an object to be surveyed using hand-held radionuclide identifiers. Hand-held radionuclide identifiers may generally be used to survey M&E of any size; constraints are only placed by the practical sizing of M&E related to the sensitive area of the probe.

D.8.7 Ruggedness

All varieties of hand-held radionuclide identifiers discussed here are typically calibrated for use in temperatures from -20 °C to 50 °C and feature seals or gaskets to prevent water ingress from rain, condensing moisture, or high humidity. Most hand-held radionuclide identifiers have a limited resistance to shock, though the durability of an instrument depends largely upon the detection media (e.g., NaI(Tl) crystals are fragile and vulnerable to mechanical and thermal shock).

D.9 Portal Monitors

Portal monitors screen access points to controlled areas, and are designed for detecting radioactivity above background. These systems are used for interdiction-type surveys, and generally do not provide radionuclide identification. Portal monitors are primarily designed to monitor activity on vehicles.

Historically, portal monitors have been used to detect radioactive materials at entrance points to scrap metal facilities and solid waste landfills, and radiological control area exit points within nuclear facilities to screen for the inadvertent disposal of radionuclides. The proximity of other items to be surveyed containing high concentrations of activity may influence the variability of the instrument background, because portal monitors survey activity by detecting small variations in ambient radiation (NRC 2002).

D.9.1 Instruments

Portal monitors can easily be arranged in various geometries that maximize their efficiencies. Most national and international standards, for example ANSI 42.35 (ANSI 2004) require both gamma- and neutron-detecting capabilities, but gamma-only versions are available. Portal monitors typically use large-area polyvinyl toluene scintillators (a form of plastic scintillators) to detect photon radiation and ^{3}He proportional tubes to detect neutrons.[8] Individual detectors may be cylindrical or flat. The detectors are usually arranged to form a detection field between two detectors, and items to be surveyed pass through the detection field (i.e., between the detectors) as shown in Figure D.3.

The system usually consists of one or more detector array(s), an occupancy sensor, a control box, and a monitoring PC. The control box and monitoring PC store and analyze alarm and occupancy data, store and analyze all gamma and neutron survey data, and may even send data through an integrated internet connection. The monitoring PC also manages software that operates multiple arrangements of detector arrays as well as third party instruments. For example, security cameras can take high-resolution images of objects that exceed a radiation screening level (Novelec 2001b).

D.9.2 Temporal Issues

Count or integration times are very short, typically just a few seconds (NRC 2002). Set-up time in the field is variable, since temporary systems may require two hours to one half-day to set up, while permanent systems may require one week to install. For vehicular portal monitor systems, objects may typically pass through the field of detection at speeds of 8 to 9.5 kilometers per hour (Canberra 2005b). Most systems use speed correction algorithms to minimize the effects of variations in dwell time (i.e., the time a given area to be surveyed spends within the detection field).

D.9.3 Spatial Issues

There are a large number of factors that affect portal monitor performance. The isotopic content of a radioactive material can determine the ease of detection. For example, high-enriched uranium (HEU) is easier to detect in a gamma portal than low-enriched uranium (LEU) or natural uranium because of the larger gamma emission rate from ^{235}U.

[8] Neutron detectors use materials that detect thermal neutrons, which may be fast neutrons that are thermalized for detection through the use of moderators.

Figure D.3 Example Portal Monitor (Canberra 2005b)

The chemical composition of a material is also important; background levels of radioactivity must also be considered. Neutron portals are an effective method for detecting plutonium in areas with large gamma backgrounds. The surface area and size of the detectors and distance between the detectors all affect the geometry and response of the system. In a large area system set-up, the closer together the detector arrays are, the better the geometric efficiencies are going to be. Finally, for each system there is a maximum passage speed through the portal that gives a counting time necessary to meet the required detection sensitivity.

D.9.4 Radiation Types

Portal monitors typically detect gamma radiation and can also be equipped to detect neutron radiation. Gamma portals often use integrated metal detectors to provide an indication of suspicious metal containers that could be used to shield radioactive materials. If the gamma radiation is not shielded adequately, the detector’s alarm will sound. Portal monitors can detect radioactive material even if it is shielded with a material with a high atomic number, like lead.

D.9.5 Range

Photon radiation can typically be measured within a detectable energy range of 60 keV up to 2.6 MeV. Neutron radiation can typically be measured within a detectable energy range of 0.025 eV up to 100 MeV. Required detection sensitivities for gamma and neutron sources are described in ANSI 42.35, Table 3 (ANSI 2004). Portal monitors provide gross counts and cannot compute quantitative measurements (e.g., activity per unit mass).

D.9.6 Scale

Most systems are designed to monitor items ranging in size from bicycles and other small vehicles to tractor trailers, railroad cars, and even passenger airplanes (Canberra 2005b). The width of the detection field (i.e., space between the detector arrays) can usually be modified.

D.9.7 Ruggedness

Portal monitors have typical operating ranges from -20 ° to 55 °C, and some systems may be functional in temperatures as low as -40 °C according to ANSI 42.35 (ANSI 2004). Portal monitors are usually designed with weatherproofing to withstand prolonged outdoor use and exposure to the elements.

D.10 Sample with Laboratory Analysis

Laboratory analysis allows for more controlled conditions and more complex, less rugged instruments to provide lower detections limits and greater delineation between radionuclides than any measurement method that may be utilized in a field setting. For this reason, laboratory analyses are often applied as quality assurance measures to validate sample data collected using field equipment.

D.10.1 Instruments

This section provides a brief overview of instruments used for radiological analyses in a laboratory setting. For additional detail on these instruments, please refer to the accompanying section references in MARLAP.

D.10.1.1 Instruments for the Detection of Alpha Radiation

- Alpha Spectroscopy with Multi-Channel Analyzer

This system consists of an alpha detector housed in an evacuated counting chamber, a bias supply, amplifier, analog-to-digital converter, multi-channel analyzer, and computer. Samples are placed at a fixed distance from the solid state partially-implanted silica for analysis, and the multi-channel analyzer yields an energy spectrum that can be used to both identify and quantify the radionuclides. The overall properties of the instrumentation allow for excellent peak resolution, although this technique often requires a complex chemical separation to obtain the best results.

- Gas-Flow Proportional Counter

The system consists of a gas-flow detector, supporting electronics, and an optional guard detector for reducing the background count rate. A thin window can be placed between the gas-flow detector and sample to protect the detector from contamination, or the sample can be placed directly into the detector. This system does not typically provide data useful for identifying radionuclides unless it is preceded by nuclide-specific chemical separations.

- Liquid Scintillation Spectrometry

Typically, samples will be subjected to chemical separations and the resulting materials placed in a vial with a scintillation cocktail. When the alpha particle energy is absorbed by the cocktail, light pulses are emitted, which are detected by photomultiplier tubes. One pulse of light is emitted for each alpha particle absorbed. The intensity of light emitted is related to the energy of the alpha. This system can provide data useful for identifying radionuclides if the system is coupled to a multi-channel analyzer.

- Low-Resolution Alpha Spectrometry

The system consists of a small sample chamber, mechanical pump, two-inch diameter silicon detector, multi-channel analyzer, readout module, and a computer. Unlike alpha spectroscopy with multi-channel analyzer, this method allows the technician to load samples for analysis without drying since the presence of moisture generally has negligible effects on the results. This method is therefore estimated to substantially reduce the time for analysis. However, the low resolution may limit the ability to identify individual radionuclides in a sample containing multiple radionuclides and thus may limit the applicability of this method (Meyer 1995).

- Alpha Scintillation Detector

This system is used primarily for the quantification of ^{226}Ra by the emanation and detection of ^{222}Rn gas. The system consists of a bubbler system with gas transfer apparatus, a vacuum flask lined with scintillating material called a Lucas Cell,[9] a photomultiplier tube, bias supply, and a scaler to record the count data.

D.10.1.2 Instruments for the Detection of Beta Radiation

- Gas-Flow Proportional Counter

The system consists of a gas-flow detector, supporting electronics, and an optional guard detector for reducing the background count rate. A thin window can be placed between the gas-flow detector and sample to protect the detector from non-fixed activity, or the sample can be placed directly into the detector. This technique does not provide data useful for identifying individual radionuclides unless it is preceded by nuclide-specific chemical separations.

[9] One end of a Lucas cell is covered with a transparent window for coupling to a photomultiplier tube and the remaining inside walls are coated with zinc sulfide.

- Liquid Scintillation Spectrometry

Typically, samples will be subjected to chemical separations and the resulting materials placed in a vial with a scintillation cocktail. When the beta particle energy is absorbed by the cocktail, light pulses are emitted, which are detected by photomultiplier tubes. One pulse of light is emitted for each beta particle absorbed. The intensity of light emitted is related to the energy of the beta. This system can provide data useful for identifying radionuclides if the system is coupled to a multi-channel analyzer. This system must be allowed to darken (i.e., equilibrate to a dark environment) prior to measurement.

D.10.1.3 Instruments for the Detection of Gamma or X-Radiation

- High-Purity Germanium Detector with Multi-Channel Analyzer

This system consists of a germanium detector connected to a cryostat (either mechanical or a dewar of liquid nitrogen), high voltage power supply, spectroscopy grade amplifier, analog to digital converter, and a multi-channel analyzer. This system has high resolution for peak energies and is capable of identifying and quantifying individual gamma peaks in complex spectra. It is particularly useful when a sample may contain multiple gamma-emitting radionuclides and it is necessary to both identify and quantify all nuclides present.

- Sodium Iodide Detector with Multi-Channel Analyzer

This system consists of a sodium iodide detector, a high voltage power supply, an amplifier, an analog to digital converter, and a multi-channel analyzer. This system has relatively poor energy resolution and is not effective for identifying and quantifying individual gamma peaks in complex spectra. It is most useful when only a small number of gamma-emitting nuclides are present or when a gross-gamma measurement is adequate.

D.10.2 Temporal Issues

Laboratory analysis is usually controlled by the turnaround time involved in preparing and accurately measuring the collected samples. The sample matrix impacts the preparation time, since soils and bulk chemicals typically require more extensive preparation than liquids or smears. Table D.2 describes the typical preparation and counting times associated with the various analytical instruments and methods described in Section D.10.1. Additional issues that may result in extended time for sample preparation and analysis are described in MARLAP.

Table D.2 Typical Preparation and Counting Times

	Typical Preparation Time	Typical Counting Time
Alpha Spectroscopy with Multi-Channel Analyzer	1 to 7 days	100 to 1,000 minutes
Gas-Flow Proportional Counter	hours to days	10 to 1,000 minutes
Liquid Scintillation Spectrometer	Minutes,[10] hours to 2 days[11]	>60 to 300 minutes
Low-Resolution Alpha Spectroscopy	minutes (DOE, 1995)	10 to 1,000 minutes
High-Purity Germanium (HPGe) Detector with Multi-Channel Analyzer	minutes to 1 day	10 to 1,000 minutes
Sodium Iodide (NaI) Detector with Multi-Channel Analyzer	minutes to 1 day	1 to 1,000 minutes
Alpha Scintillation Detector	1 to 4 days; 4 to 28 days[12]	10 to 200 minutes

D.10.3 Spatial Issues

This section addresses issues related to detector-M&E geometry and provides information on the range of impacts resulting from dissenting geometries between the calibration source and the measured sample. Other topics may include detector dimensions and problems positioning instruments.

[10] Minimal preparation times are possible if the sample does not require concentration prior to being added to the liquid scintillation cocktail vial.

[11] Longer preparation times are necessary for speciation of low-energy beta emitters.

[12] Longer count times represent the necessary time for in-growth of ^{222}Rn for ^{226}Ra analyses.

D.10.3.1 Alpha Spectroscopy with Multi-Channel Analyzer

Sample geometry (lateral positioning on a detector shelf) in some detectors may be a small source of additional uncertainty. Uncertainty in the preparation of the actual calibration standards as well as the applicability of the calibration standards to the sample analysis should also be considered.

D.10.3.2 Gas-Flow Proportional Counter

Even deposition of sample material on the planchette is critical to the analytical process. In some analyses, ringed planchettes may aid in the even deposition of sample material. An uneven deposition may result in an incorrect mass-attenuation correction as well as introducing a position-dependent bias to the analysis. The latter situation arises from the fact that gas-flow proportional counters are not radially-symmetric, so rotation of an unevenly deposited sample by 45 degrees may drastically change the instrument response.

D.10.3.3 Liquid Scintillation Spectrometer

For gross counting, samples (e.g., smears and filters) can be placed directly into a liquid scintillation counter (LSC) vial with liquid scintillation cocktail, and counted with no preparation. There are samples with more complicated matrices that require chemical separation prior to being placed and counted in LSC vials. Calibration sources are also kept and counted in these vials, so the geometry of the source and the sample compared to the detector are generally similar.

D.10.3.4 Low-Resolution Alpha Spectroscopy

Sample geometry (lateral positioning on a detector shelf) in some detectors may be a small source of additional uncertainty. Uncertainty in the preparation of the actual calibration standards as well as the applicability of the calibration standards to the sample analysis should be considered.

D.10.3.5 High-Purity Germanium Detector with Multi-Channel Analyzer

Geometry considerations are most important for spectroscopic gamma analyses. Sample positioning on the detector may significantly affect the analytical results, depending on the size and shape of the germanium crystal. Moreover, the instrument is calibrated with a source that should be the same physical size, shape, and weight as the samples to be analyzed.[13] Discrepancies between the volume or density of the sample and the source introduce additional uncertainty to the analytical results.

Sample homogeneity is a critical factor in gamma spectroscopy analyses, particularly with relatively large samples. For example, sediment settling during the course of analysis of a turbid aqueous sample will result in a high bias from any activity contained in the solid fraction. Likewise, the positioning of areas containing elevated activity in a solid sample will create a bias in the overall sample activity (the activity will be disproportionately high if the particle is located at the bottom of the sample, and the activity will be disproportionately low if it is located at the top of the sample).

D.10.3.6 Sodium Iodide Detector with Multi-Channel Analyzer

The spatial considerations for NaI detectors are the same as those listed above for high-purity germanium detectors.

D.10.3.7 Alpha Scintillation Detectors

Accurate sample analysis depends heavily on the complete dissolution of the ^{226}Ra or other radionuclides of interest in the bubbler solution. Adequate sample preparation will help ensure that spatial issues do not influence results, as the apparatus itself minimizes any other potential geometry-related sources of error or uncertainty.

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[13] Some software packages allow a single calibration geometry to be modeled to assimilate the properties of other geometries.

D.10.4 Radiation Types

Table D.3 describes the types of radiation that each laboratory instrument and method can measure.

Table D.3 Radiation Applications for Laboratory Instruments and Methods

	Alpha	Beta	Photon	Neutron	Differentiate Radiation Types	Identify Specific Radionuclides
Alpha Spectrometry with a Multi-Channel Analyzer	GOOD	NA	NA	NA	NA	GOOD
Gas-Flow Proportional Counter	GOOD	GOOD	POOR	NA	FAIR	POOR
Liquid Scintillation Spectrometer	POOR	GOOD[14]	POOR	NA	FAIR	FAIR
Low-Resolution Alpha Spectroscopy	GOOD	NA	NA	NA	NA	FAIR[15]
High-Purity Germanium Detector with Multi-Channel Analyzer	NA	NA	GOOD	NA	NA	GOOD
Sodium Iodide Detector with Multi-Channel Analyzer	NA	NA	GOOD	NA	NA	FAIR
Alpha Scintillation Detector	GOOD	NA	NA	NA	NA	FAIR

Notes:

GOOD The instrumentation and measurement technique is well-suited for this application

FAIR The instrumentation and measurement technique can adequately perform this application

POOR The instrumentation and measurement technique may be poorly-suited for this application

NA The instrumentation and measurement technique cannot perform this application

D.10.5 Range

All of the instrumentation discussed here has physical limitations as to the amount of activity that can be analyzed. This limitation arises primarily from the ability of the detector to recover after an ionizing event, and the speed with which the component

[14] This system is designed for the detection of low-energy beta particles.

[15] The low resolution may limit the ability to identify individual radionuclides in a sample containing multiple radionuclides.

electronics can process the data. Typically, a count rate on the order of 10^6 counts per second taxes the physical limitations of most detectors. Other practical considerations, (such as the potential to impact the detector with non-fixed activity) often override the physical limitations of the counting system.

There are energy range limitations as well. For example: window proportional counters are poor choices for very low energy beta emitters; some gamma spectrometers have poor efficiencies at low energies; and some systems are not calibrated for high-energy gammas. Table D.4 describes the energy range that each instrument and method can be used to determine, and the maximum activity per sample that the method can be used to count.[16]

Table D.4 Typical Energy Ranges and Maximum Activities

	Energy Range	Maximum Activity
Alpha Spectrometry with Multi-Channel Analyzer	3 to 8 MeV	<10 Bq (<270 pCi)
Gas-Flow Proportional Counter	3 to 8 MeV (α) 100 to 2,000 keV (β)	35 Bq (946 pCi)
Liquid Scintillation Spectrometer	>3 Mev 15 to 2,500 keV (β); >1.5 MeV (β)[17]	100,000 Bq (2.7 μCi)
Low-Resolution Alpha Spectrometry	3 to 8 MeV (α)	<10 Bq (<270 pCi)
High-Purity Germanium (HPGe) Detector with Multi-Channel Analyzer	50 to >2,000 keV (P-type detector); 5 to 80 keV (N-type detector)	370 Bq (10,000 pCi)
Sodium Iodide (NaI) Detector with Multi-Channel Analyzer	>80 to 2,000 keV	370 Bq (10,000 pCi)
Alpha Scintillation Detector	All α emission energies	<10 Bq (<270 pCi)

[16] David Burns, Paragon Analytics, Inc., private communication with Nick Berliner, Cabrera Services, Inc., March 2005.

[17] Very high-energy beta emitters may be counted using liquid scintillation equipment without liquid scintillation cocktails by the use of the Cerenkov light pulse emitted as high energy charged particles move through water or similar substances.

D.10.6 Scale

There is no minimum sample size required for a given analysis. Smaller sample sizes will necessarily result in elevated detection limits. Minimum sample sizes (e.g., 0.1 gram) may be specified in order to ensure that the sample is reasonably representative given the degree of homogenization achieved in the laboratory. Typical liquid and solid sample sizes are noted in Table D.5.

Table D.5 Typical Liquid and Solid Sample Sizes

	Typical Liquid Sample Size	Typical Solid Sample Size
Alpha Spectrometry with Multi-Channel Analyzer	1 liter	2 grams; 50 grams[18]
Gas-Flow Proportional Counter	1 liter	2 grams
Liquid Scintillation Spectrometer	<10 milliliters; 1 liter[19]	<0.5 grams; 500 grams
Low-Resolution Alpha Spectrometry	1 liter	2 grams; 50 grams[17]
High-Purity Germanium (HPGe) Detector with Multi-Channel Analyzer	4 liters	1 kilogram
Sodium Iodide (NaI) Detector with Multi-Channel Analyzer	4 liters	1 kilogram
Alpha Scintillation Detector	1 liter	2 grams

D.10.7 Ruggedness

Ruggedness does not hold relevance to laboratory analyses, because they are performed in a controlled environment that precludes the instrumentation from being exposed to conditions requiring durability.

[18] The use of sample digestion processes allows the processing of larger sample masses.

[19] Direct depositing of sample material into the scintillation cocktail limits the sample size to the smaller samples sizes noted; prepared analyses may use substantially larger sample quantities as noted (this applies to both liquid and solid sample matrices).